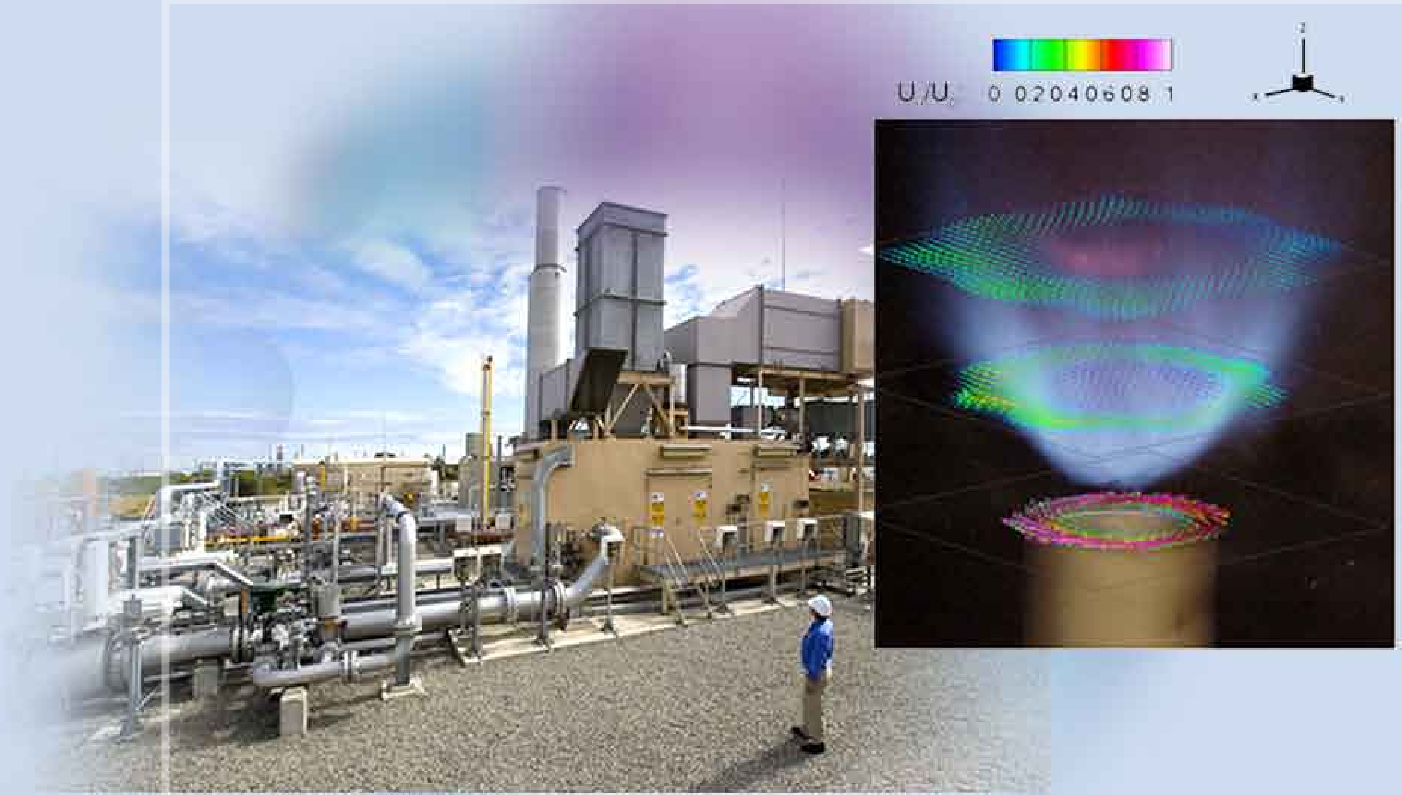
2007 R&D 100 Award Entry

Low Swirl Injector for Fuel Flexible Near Zero Emissions Gas Turbines



Lawrence Berkeley National Laboratory

Berkeley Lab

2007 R&D 100 AWARDS ENTRY FORM

1 Submitting Organization

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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

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2 Joint entry with:

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3 Product name:

Low Swirl Injector for Fuel Flexible Near Zero Emissions Gas Turbines

4 Briefly describe (25 words or less) what the entry is (e.g. balance, camera, nuclear assay, etc.)

The Low Swirl Injector is an elegant, lower cost, durable combustion technology for gas turbines. It efficiently generates electricity from hydrocarbons and hydrogen with near zero emissions.

5 When was this product first marketed or available for order? (Must have been first available in 2005.)

This technology was available for license by industry in 2006.

6 Inventor or Principal Developer (List all developers from all companies)

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7 Product price

To be determined by licensee.

8 Do you hold any patents or patents pending on this product?

U.S. Patent No. 5,735,681, issued April 7, 1998, Ultra-lean Low Swirl Burner.

U.S. Patent No. 5,879,148, issued March 9, 1999, Mechanical Swirler for a Low-NO_x Weak-Swirl Burner.

9 Describe your product's primary function as clearly as possible. What does it do? How does it do it? What theories, if any, are involved?

The Low Swirl Injector for Fuel Flexible Near Zero Emissions Gas Turbines (LSI) significantly reduces greenhouse gas emissions and pollution from the production of electricity, which accounts for 40 percent of energy use in the United States. It exploits a combustion technology developed at Lawrence Berkeley National Laboratory and adapted to the marketplace by Solar Turbines, Inc. (Figs. 1 & 2). It emits less than 2 parts per million (PPM) NO_x (corrected to 15 % O2[1]) by exploiting a novel counterintuitive combustion concept that is fundamentally and radically different than the traditional high-swirl combustion method used in all dry low-NO_x (DLN) combustors. The LSI produces low emissions with no cost premium, no need for substantial redesign of the basic gas turbine, and no need for expensive materials such as catalysts. It also has the potential to increase turbine system efficiency and performance. The LSI technology dispels a long held notion that emission reduction is complex and costly. This pioneering technology holds tremendous promise for producing near zero NO_x emissions, and eventually, clean, carbon-neutral[2] and ultimately zero carbon emission electricity.

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[1] A factor used to adjust measured gas turbine emission readings to an emission rate at a reference oxygen (O_2) level.

[2] Carbon-neutral fuels are those that add no net greenhouse gases to the atmosphere when burned.

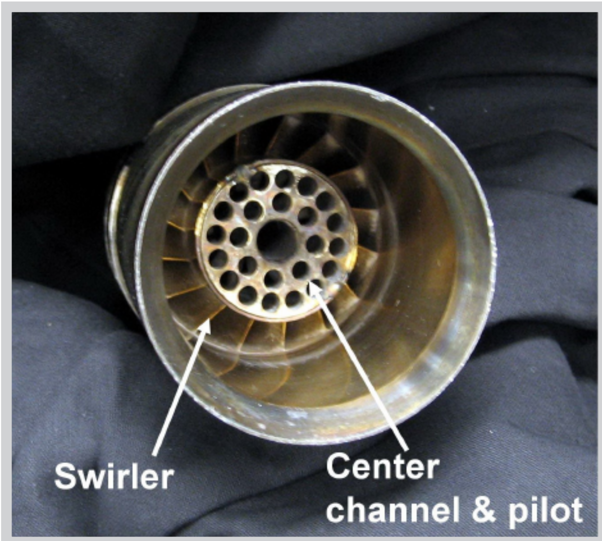

Figure 1 The LSI design is deceptively simple. Its annulus vane swirler resembles the conventional high-swirl injectors. But the circular openings at its center channel defy convention. Flow through these holes promotes the formation of flow divergence which is the foundation of the low swirl flame stabilization method. The divergent flow provides a stable aerodynamic configuration for the premixed flame to self-propel and turbulence intensity provides the feedback for the flame to burn faster or slower as load changes.

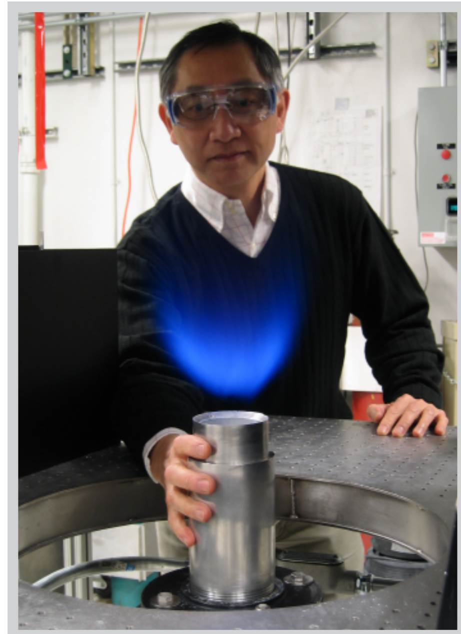

Figure 2 Application of sophisticated laser diagnostics on laboratory LSI flames firing in the open provided much of the basic knowledge needed to scale the technology to operate at the high temperature and high pressure conditions of gas turbines. Here, inventor Robert Cheng demonstrates that LSI stays cool to the touch because the flame is completely lifted from its body.

LSI's unique fuel flexible capability means that combustion turbines running on natural gas now will be able to run on carbon-neutral bio- or waste gases.

The greatest impact of the LSI technology will be realized when it is employed in advanced turbines for coal derived syngases and hydrogen in Integrated Gasification Combined Cycle (IGCC) coal-based power plants. The U.S. Department of Energy and the power industry consider IGCC power plants that capture and sequester CO_2 to be the FutureGen power plant for meeting the nation's growing demand for clean electricity. FutureGen is a DOE initiative to build the world's first zero-emissions fossil fuel power plant, which will use the IGCC approach to produce hydrogen. The hydrogen is separated from a concentrated CO_2 stream that is then captured for subsequent sequestration. Work is underway to develop LSI for the high hydrogen fueled IGCC turbines. This technology, when deployed in all IGCC power plants of the future, has the potential to help eliminate greenhouse gas emissions by an average of 1.8 million tonnes of CO_2 and 4000 tonnes of NO_X per power plant per year while saving an average of $7.5 M of the capital investment on turbine exhaust treatment technologies per plant.

Development of the Fuel Injector

Sandwiched between the compressor and the turbine sections, the fuel injector of the combustor in a gas turbine is the heart of power generation (Fig. 3). It has several critical functions, including: maintaining an efficient, stable, and safe flame, as well as mitigating the emissions of undesirable pollutants. Despite its prominent role, the injector's physical size and form and its operating conditions are strictly dictated by the configuration and throughput conditions of the compressor and turbine. In the 1980s, the advent of high-swirl dry low-NO_X (DLN) technologies based on lean premixed combustion brought down the emissions of NOx from well over 100 ppm to the current <25 ppm, which is the limit for many parts of the US. Further DLN development to achieve the proposed ultra-low NO_X levels of <9 ppm required elaborate and very tight controls, and monitoring of fuel/air mixing and flame stability. To reach the near zero emissions goal of <2 ppm being implemented

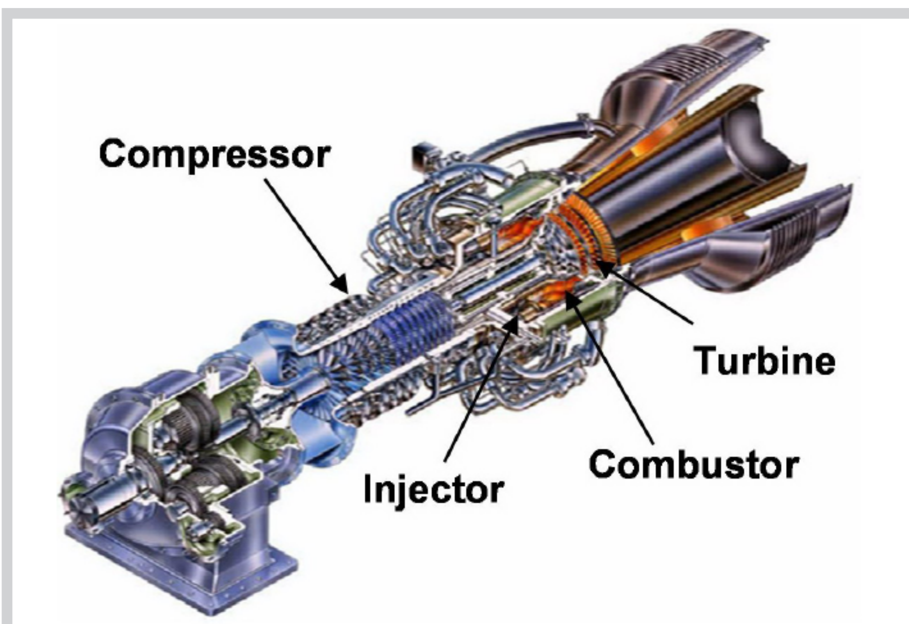

Figure 3 A cutaway view of Solar Turbines' Taurus 70 gas turbine shows that the injectors (12 total) are mounted behind a network of fuel lines and control valves. Space is a premium around the so-call "hot zone". Any change in the size and form of the injector or the combustor requires a complete redesign of the engine layout. The situation is the same for all other gas turbines, forcing many manufacturers to opt for expensive trail-pipe exhaust cleanup with catalysts.

in non-attainment areas in the US[3], most industrial experts consider catalytic combustor or catalytic exhaust gas treatments (Selective Catalytic Reduction—SCR) to be the only viable options and lament that the near zero emissions goal is synonymous with high cost and shortened life-cycle.

The Low Swirl Injector for Flexible Fuel Near Zero Emissions Gas Turbine uses the low swirl flame stabilization method conceived and developed by Dr. Robert Cheng at Lawrence Berkeley National Laboratory. This novel method exploits the wave property of lean premixed combustion. It is the fundamental opposite of the high swirl combustion method practiced for almost a century[4]. Yet the size and form of the LSI is compatible with current turbine designs. The LSI, as developed for the natural gas-powered Solar Turbines Taurus 70 engine, is a drop-in replacement that does not require fundamental redesign of the combustor section and has no impact on its operating, life, and maintenance cycles.

Reliance on Combustion and Need for Lower Emissions

Combustion provides 83% of the energy consumed in the U.S., and natural gas, a traditional energy source for industrial, commercial and residential heating, has fast become a fuel of choice for peak demand electricity generation via gas turbines. Compared to the traditional pulverized-coal boilers/steam turbine power plants, gas turbine power plants have significantly lower emissions of NO_x and greenhouse gases and provide greater flexibility in generation capacity. All power generation gas turbines are subject to stringent air-quality rules being implemented in urban areas world-wide. A steady rise in natural gas utilization in the U.S. has also stimulated a demand for imported liquid natural gas (LNG) whose content variability causes significant problems for gas turbines that are tuned precisely to achieve high performance and ultra-low emissions. A significant advantage of the LSI is that it is scalable to gas turbines of all sizes and is fuel flexible, capable of burning almost all gaseous hydrocarbons, from blended hydrocarbon such as landfill gases, biomass gases, and refinery gases, to pure hydrogen. It is therefore a carbon-neutral technology when fueled with renewable fuels, and a greenhouse gas-reduction technology when developed for turbines fueled with syngases and pure hydrogen for the next generation of IGCC coal power plants with CO_2 capture and sequestration.

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[3]A Non-Attainment Area is an area defined by EPA that does not meet one or more of the National Ambient Air Quality Standards for the criteria pollutants designated in the Clean Air Act. These areas include California, Texas and most of North Eastern States.

[4]High swirl combustion is found in all gas turbines and aircraft engines, and a majority of industrial burners and most commercial heating systems.

Novel Design Theory

Lean premixed combustion is the foundation for the DLN method in all modern gas turbines. It burns gaseous fuels mixed thoroughly with an amount of air that exceeds the quantity needed to consume the fuel (i.e. excessive air combustion or fuel-lean combustion). This approach inhibits NO_x formation by lowering the flame temperature. Doing so has many undesirable consequences including high carbon monoxide (CO) emissions, incomplete combustion, and most significantly, flame instability, which can trigger severe pressure oscillations that can damage or cripple engines. The low swirl injector (Fig.1) offers an elegant, unexpected solution to circumvent these problems by exploiting a novel design theory that defies conventional scientific theory in this area.

Conventional combustion theory stresses the critical role of the recirculation zone of a high swirl flow to hold and to continuously supply a source of heat and active chemical species to ignite the lean premixed flame. The low swirl flame stabilization method, developed by Dr. Cheng, leader of the Combustion Technology Group at Berkeley Lab, defies this theory by taking an opposite approach. It shows that lean premixed flame does not require a continuous ignition source because it can self propel. This fundamental flame property can only be exploited by allowing the flame to self-propel in the divergent flow generated in a low swirl flow. For more information, see Appendix B for a list of references and selected reprints, and Appendix C for more detail on the technology.

Figure 4 The University of Illinois at Chicago has a cogeneration plant with three T70 gas turbines to produce electricity and steam. LSI can save up to $0.75M for a similar installation in the non-attainment areas that requires <2.5 ppm NO_x emissions.

Successful demonstration of LSI in the Taurus 70 Turbine

The LSI has been developed for Solar Turbines' Taurus 70 engine (Figs. 3 & 4) that is rated for 7.7 MW of electrical production from natural gas. This engine is currently rated for NO_x emissions between 15 to 25 ppm and the company is interested in developing a low-cost combustion technology to reduce its emission to below 5 ppm and ultimately the near zero goal of <2 ppm. Of the four competing technologies in DOE's program (see matrix), the LSI is the only one that does not involve high-cost sophisticated materials (i.e. precious metals and high temperature metal foams).

One of the significant accomplishments in LSI development is utilizing the $SoLoNO_x$ swirler by converting it to operate in low swirl mode. Using an existing part is a significant cost-saving opportunity. Moreover, the LSI is much simpler and less costly to manufacture than $SoLoNO_x$ due to design improvements that enable the elimination of high cost ceramics and fabrication procedure. The LSI is configured to be a drop-in device—no fundamental redesign of the Taurus 70 was needed to achieve the near zero emissions (Figure 5). Tests in a high-pressure chamber

Figure 5 The LSI is a drop-in replacement for the $SoLoNO_x$ injector. It is designed to retrofit the Taurus 70 engine to attain <5 ppm NO_x. A five times reduction from the Taurus 70's original performance target of <25 ppm NO_x The $SoLoNO_x$ injector produces a flame that attaches to a center hub that is embedded with intricate cooling circuits.

simulating a gas turbine environment showed emissions of NO_x and CO <2 ppm (Fig. 5 from [Johnson et al., 2005]). A T70 engine fitted with twelve LSI demonstrated outstanding performance characteristics in terms of control, start-up, idling, and load change while achieving the emissions goal of <5 ppm NO_x.

10A List your product's competitors by manufacturer, brand name and model number.

1. Surface Stabilized Combustion—Under development by Alzeta Corp.
2. Rich Catalytic Lean Injection combustion—Under development by Precision Combustion Inc.
3. Fully Catalytic Combustion—Withdrawn from development by Catalytica Combustion in 2004
4. High-swirl combustion with Selective Catalytic Reduction (SCR)—Conventional approach available from vendors such as Wahlco, Inc. Advanced Environmental Systems and CRI Catalyst Company.

10B Supply a matrix or table showing how the key features of your product compare to existing products or technologies. Include both numerical and descriptive comparisons.

		LBNL Low-Swirl Injector (LSI)	Surface Stabilized Combustion (Alzeta Corp.)	Rich Catalytic Lean Injection Combustion (Precision Combustion Inc.)	Catalytic Combustor (Catalytica Combustion)	Current combustion technology with SCR (exhaust gas cleanup)	Competitive Advantage of Low Swirl Injector
Performance	**Low-cost solution for near zero emission turbines**	Yes—advanced flame stabilization relative to conventional high swirl approach	No—utilizes narrow flow passages through higher cost and less durable porous material for flame holding	No—a variation of rich/lean staged combustion using expensive catalytic partial oxidation	No—a well-known surface catalytic reactions to sustain lean combustion that is too expensive to be practical	No—an expensive post combustion exhaust gas treatment for conventional turbines adding \$30 to \$50/kW to the cost of the system	Very affordable technology with no added cost to manufacture, operate, or maintain gas turbines
	Anticipated load range for <5 ppm NO_x	25% to full load	50% to full load	75% to full load	90% to full load	75% to full load	Ultra-low emissions at extended load range
	Impact on turbine operation	None—startup, shut down, and load following same as current engines	Moderate—restricted operating envelope, slower startup and transient response	High—catalyst requires a long time to warm up and has poor response to transients	High—catalyst requires a long time to warm up and has poor response to transients	Moderate—SCR controls must be integrated with turbine controls	Fully compatible with control systems for ease of integration into electric power grid and rapid response for fluctuating power needs
	Anticipated hours of operation between inspection/ overhaul	>30,000, expected to last longer than current engines due to minimal material heating	8,000—delicate porous materials receive direct heat from the attached flame	8,000—catalysts lose their effectiveness over time	< 8,000—catalysts lose their effectiveness over time	8 000 to 16,000—catalysts require periodic replacement	No impact on the maintenance schedule or cost to an engine and reduces NO_x by almost a factor of 10
	Demonstrated with renewable fuels	Yes—gaseous fuels with Wobbe indices from 4,000 to 18,000 kcal/Nm^3	No	No	No	No—turbine has to be redesigned for different fuels	Enabling technology for carbon-neutral electricity generation

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Performance	**Demonstrated potential for firing with hydrogen**	Yes—requiring a slight change in LSI swirl number	No	No	No	No	Enabling technology for IGCC coal-base power plant with CO_2 capture and sequestration
Impact on Turbine System and Manufacturing	**Engine modification needed to accept new technology**	None—drop-in replacement for current turbines.	Requires combustor redesign to accommodate intrusion of porous material into the chamber	Requires combustor redesign to accommodate large catalytic reactors	Requires completely new and larger combustor and also impacts compressor and turbine sections	Large external system required downstream of turbine. More complex turbine controls required	Direct integration into current turbines without the need for expensive redesign, downstream systems or more complex controls
	Fabrication cost relative to dry low NO_x (DLN) high-swirl injector	-30 %—less than DLN due to a simpler design made from stainless steel	100%—higher than DLN due to costly high temperature porous materials and a new premixer	200%—higher than DLN due to precious metal catalyst embedded in ceramic substrate	400 % higher than DLN due to significant amount of precious metal catalyst needed	Engine uses DLN but system cost increases due to the SCR system requiring precious metal and ceramic substrate	Lowest cost option requiring fewer service interruptions for periodic inspection of material degradation
	Minimal or no change in gas turbine manufacturing process	Yes—uses materials and components from current $SoLoNO_x$	No—tight control on dimensions required. Complex, handling of fragile and expensive materials needed	No—needs careful assembly of catalyst	No—complex design including pre-heaters	No—system operations	No retooling necessary with almost zero add-on investment cost in technology implementation.
	Reduced the complexity of the gas turbine system	Yes—a simpler design than current DLN due to elimination of active cooling circuit	No— an elaborate premixer is needed to maintain mixture homogeneity	No—requires two fuel supply lines that requires tight controls, and size of hardware much larger than current DLN injector	No—very big footprint, nearly twice as large	No—increases footprint	No additional investment to fabricate new hardware. Design is less complicated than current DLN technology

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R&D Cost and Future Prospects	**Design simplicity & low cost to scale up and scale down**	Yes—scaling rules developed and unit cost decreases significantly for large engines	No—material cost of injector scales directly with power output and combustor requires redesign	No—the amount of high-cost catalyst and ceramic substrates is directly proportional to the power output	No	No	LSI operates at a very wide range of conditions. Its design and physical size change slightly for gas turbines of 70kW to over 200 MW
	Efficiency enhancement potential	Yes—low back pressure design	No	No	No	No	Compatible with advanced high efficiency recuperated turbines
	Development cost, $, total U.S. and state government R&D investment 1996–2006	1M	7.6M	5M	7.9 M (project withdrawn in 2004)	n/a	Scientific underpinning reduces design iterations and test cycles, and streamlines integration into the turbine

10C Describe how your product improves upon competitive products or technologies.

Of the technologies currently on the market, and those in development, the LSI is the only one that is a plug-in for existing turbines and yet its development and implementation costs are only a fraction of the more elaborate and less promising competing technologies. LSI technology is simple and scalable through the entire range of turbines sizes, does not require expensive computational fluid dynamics for design guidance, and requires no special materials or elaborate combustion control protocol.

Very cost effective solution to lower NOx and other greenhouse gas emission. The technology reduces pollutants by a simple and elegant aerodynamic method. It exploits a basic property of premixed turbulent flames to reduce nitrogen oxides emissions to below 2 parts per million (corrected to 15 percent O_2) to help air quality districts meet stringent air quality standards. If implemented in gas turbines for natural-gas electric generators and power plants it will lower their NO_x emissions by 5 to 10 times. For future coal-fired IGCC power plants, LSI will play a critical role in removing 4000 tons of NO_x and 1.8 million tons of CO_2 per plant per year in the U.S.

Fuel Flexible. The technology allows gas turbine operators to choose among a variety of different fuels including natural gas, propane, waste gases, biogases, and petroleum refinery gases. Use of gaseous hydrocarbon fuels generated through carbon-neutral processes helps reduce net greenhouse gas emissions to the atmosphere, and therefore, reduces global warming potential. LSI gas turbines can be designed to operate on hydrogen and natural gas to allow the IGCC coal-fired power plant a valuable backup fuel option that can provide greater operational and economic benefits.

The LSI has excellent fuel flexible capability because its operating mechanism is tolerant of variations in flame properties. Fuel flexible capability has been verified at Solar Turbines, where it was tested with fuels simulating low-Btu biomass and land-fill gases. Tests at the National Energy Technology Laboratory also demonstrated LSI's ability to burn fuels with H_2 content exceeding 85%. Its ability to operate with pure H_2 and syngases has been demonstrated in laboratory experiments [Cheng and Littlejohn, 2007].

Scalable. The low swirl technology can be scaled with little additional effort for use in any size gas turbine, from microturbines generating 70 kW to turbines used in 250 MW plants. An extraordinary aspect of the T70 LSI development process is a lack of extensive reliance on costly and time-consuming computational fluid dynamics (CFD) analysis. CFD is not needed for LSI development because its flame position, flowfields, and emissions are well characterized and predictable by a linear analytical model (see Appendix C).

Low cost. Because of its simple and scalable design that does not require fragile, delicate or high cost specialized materials, the Berkeley Lab/Solar LSI costs less to manufacture and is more durable than Solar Turbine's current DLN high-swirl injector known as $SoLoNO_x$. Gas turbines outfitted with LSI will cost no more to operate and maintain than the high-swirl version. Compared to the estimated additional capital cost of $30 to $50 per kW for the Selective Catalytic Reduction options, the LSI will provide tremendous cost relief for the next generation of environmentally benign electrical power equipment. Perceived high cost and lower performance are often why plant operators reject environmentally lower impact technologies. The LSI overcomes both of these objections. The Low Swirl Injector's near zero emissions and affordable high performance radically changes the landscape of environmental protection.

Available. Quick startup of gas turbines is the reason for their primary role in providing on-demand power. LSI is a near zero emission technology that has the same start-up and transient characteristics as current combustion technology, but with a much larger turndown range to provide excellent power availability and load flexibility to cater to rapidly changing grid demand and air-quality regulations.

Durable. Gas turbines using low swirl injectors will last longer and cost less to maintain because the low swirl flame floats at a slight distance away from the injector. The injector does not overheat as in conventional injectors, reducing wear and tear on its materials.

No substantive redesign of gas turbine technology. The low swirl injector can be implemented in gas turbines without the need for substantial redesign of the turbine hardware and its control protocol. This contributes to keeping the implementation cost low, and increasing the flexibility and performance of the turbine.

Significant economic benefit to turbine operators. Higher cost and lower performance are the main reasons operators reject environmental technologies. An LSI gas turbine with near zero emissions and better performance can significantly alter the landscape for environmental preservation.

Potential for efficiency increase. The back pressure created by the injector (i.e. pressure drop) reduces the overall efficiency of the engine. Because the LSI is a low-pressure drop design compared to its competitors, further reductions in LSI pressure drop are possible. Thus, a new engine that is designed around the LSI can have a significant energy efficiency advantage while maintaining near zero emissions. Another potential energy efficiency improvement is the use of LSI in recuperated engines that utilizes waste heat from the turbine exhaust to preheat the intake air. The LSI design can be adjusted for operating at these higher temperatures without sacrificing emissions and engine performance.

11A Describe the principal applications of this product.

The Low Swirl Injector for Flexible Fuel Near Zero Emissions Gas Turbine is designed for use in gas turbines from 70 kW for on-site power generation to well over 250 MW in power plants burning gaseous fuels such as hydrocarbons (including natural gas, liquified natural gas, waste gases, petroleum production and refinery gases, and biogases), syngases (a blend of H_2 and CO produced by gasification of coal), and pure hydrogen. It can also be developed for dual fuels operation (i.e. firing with either gaseous or liquid fuels such as diesel, bio diesels, jet-A fuels and light oil). LSI technology can potentially apply to all natural gas generating capacity in the U.S. and internationally. There are almost 5,500 natural gas generators in the U.S. according to the Department of Energy, with a nameplate capacity of almost 440,000 MW.

11B List all other applications for which your product can now be used.

The LSC is based on the low swirl combustion technology (LSC) which is fully scalable. LSC can be used to reduce the emissions of any type of stationary combustion systems from hot water heaters in homes to burners and boilers for industrial purposes, to the small medium and large scale power-generation gas turbines described in this application. In all scaled applications, the LSC results in substantially reduced air pollutant emissions compared to conventional technology, and permits the fuel switching capability that allows the burner to use gaseous fuels generated using a carbon-neutral processes, including bio- and waste gas, and hydrogen. LSI technology can potentially reduce emissions in all home water heaters, as well as industrial burners, in the U.S. and internationally. Of the107 million households in the U.S., 58 million have natural gas-based water heaters that use 1.15 quadrillion Btus per year according to the Department of Energy.

Figure 6 Maxon Corp's M-PAKT (0.5–3.5MMBtu/hr.) and Optima SLS (12–50 MMBtu/hr.) burners utilize low swirl combustion technology to help manufacturing industries achieve near zero < 2.5 ppm NO_x (@15% O_2).

Low swirl combustion technology is currently being used in product lines of industrial burners sold by Maxon Inc. (See Fig. 6) Companies that manufacture boilers and hot-air furnaces for residential applications have expressed interest in low swirl combustion technology.

12 Summary. State in layman's terms why you feel your product should receive an R&D 100 Award. Why is it important to have this product? What benefits will it provide?

Low Swirl Combustion for Fuel Flexible Near Zero Emissions Gas Turbines (LSI) is a tremendously promising, elegant, cost-effective technology for significantly reducing the emissions of greenhouse gases, including nitrogen oxides from electricity generation. A significant benefit of low swirl technology is its scalability (up or down) and fuel flexibility. Gas turbines of all sizes, ranging from 70kW to well over 250 MW using LSI, can burn a variety of gaseous hydrocarbons including natural gas, liquefied natural gas, petroleum production and refinery gases, waste gases, and biogases and still meet the stringent <2.5 ppm NO_x emission limit. The later two gaseous fuels are carbon-neutral renewable fuels that are fast becoming a significant component of greenhouse gas reduction schemes.

LSI is a critical enabling technology for Integrated Gasification Combined Cycle coal power plants with CO_2 capture. It will allow these plants to produce near zero emissions by the year 2025. In the next 15 years, the United States is currently projected to build 31 Gigawatts of new power generation capacity. Coal-based IGCC plants will be the technology of choice to significantly curtail and eventually eliminate greenhouse gas emissions. LSI will provide the advanced combustion technology that will allow these power plants to meet the efficiency, emissions, and capital and operational cost goals to provide energy for a growing economy without contributing greenhouse gases to the environment. This technology, when deployed in all IGCC power plants of the future, has the potential to help eliminate greenhouse gas emissions by an average of 1.8 million tones of CO_2 and 4000 tones of NO_x per 250 MW power plant per year and save an average of $7.5M capital investment on costly alternative NO_x control technology. Low-swirl technology is a critical tool in the global battle to reduce greenhouse gas emissions and forestall climate change.

ORGANIZATION DATA

13 Contact person to handle all arrangements on exhibits, banquet, and publicity.

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List of Attachments
2007 R&D 100 Awards
ENTRY—Low Swirl Injector for Fuel Flexible Near Zero Emission Gas Turbines

A. Letters of Support

- Timothy Bridgeman, Director of Engineering, Solar Turbines
- Anil Gulati, Gas Turbine Combustion, Siemens Power Systems
- David Dewis, President & COO, Elliott Energy Systems
- Leonard Angello, Combustion Turbine Technology Manager, Electric Power Research Institute

B. List of Publications and Selected publications

Internet sites:

- Resource page on low swirl flame stabilization method: http://eetd.lbl.gov/aet/combustion/LSC-Info/
- Web-based discussion on low swirl combustion November 8, 2996 http://eetd.lbl.gov/aet/combustion/LSC-Webcast/LSI%20web-discussion.html
- Overview of DOE-EERE Low Emissions Turbine Projects: http://www.eere.energy.gov/de/industrial_turbines/projects_low_emission.html
- DOE-EERE Distributed Energy Resources Peer-Reviews: http://www.eere.energy.gov/de/conf-02_micro_indgas_pr.html http://www.eere.energy.gov/de/conf-03_der_peer_review.html http://www.advancedceramics.org/Newsletter/4-3-02-Haught.pdf

C. Technical Appendix

2007 R&D 100 Awards
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Near Zero Emission Gas Turbines

Appendix A

Letters of Support

- Timothy Bridgeman, Director of Engineering, Solar Turbines
- Anil Gulati, Gas Turbine Combustion, Siemens Power Systems
- David Dewis, President & COO, Elliott Energy Systems
- Leonard Angello, Combustion Turbine Technology Manager, Electric Power Research Institute

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Appendix B

List of Publications and Selected publications

R. K. Cheng & D. Littlejohn, "Laboratory Study of Premixed H2-Air & H2-N2-Air Flames in a Low Swirl Injector for Ultra-Low Emissions Gas Turbines," *Proceedings of GT2007*, Paper GT2007-27512.

*D. Littlejohn & R.K. Cheng "Fuel effects on a low swirl injector for lean premixed gas turbines," *Proceedings of the Combustion Institute* 2007, 31, (3155-3162).

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*Included in this Appendix

2007 R&D 100 Awards
ENTRY—Low Swirl Injector for Fuel Flexible
Near Zero Emission Gas Turbines

Appendix C

Technical Appendix

LSI Technology Background

Until now, all DLN gas turbine injectors have used the high-swirl flame stabilization method, which evolved from the non-premixed combustion technology found in older and more polluting gas turbines. This traditional method uses a recirculating region (i.e. back flow or reversed flow) to trap and retain a portion of the hot combustion products to ignite fresh reactants. Generations of combustion engineers have been trained to design injectors with swirl intensities well above the vortex breakdown threshold[1] to ensure strong recirculation. Combustion researchers are still developing theories and computational methods on high swirl flames to predict the strengths and size of the recirculation zone to support the engineering designs.

The LSI adopts the opposite approach by operating at swirl intensity well below the vortex breakdown threshold. It produces a non-recirculating flow characterized by a flow divergence region where the lean premixed turbulent flame self-propels and burns at its most natural state. The basic operating principle exploits the most fundamental property of premixed combustion—the premixed flame behaves as a "propagating wave" that moves through and consumes the reactants at a flame speed controlled by mixture composition, and turbulence intensity[2]. The flowfield of the LSI can be aerodynamically "tuned" to accommodate the turbulent flame speed. And turbulence intensity provides the feedback for the flame to burn faster and slower with load change. This theory is fundamentally different than the flame-holding approach of the traditional high-swirl method.

The combustion research and equipment manufacturing communities were highly skeptical of this new approach mainly because low swirl flows were deemed irrele-

[1]Vortex breakdown is a precursor to flow reversal and the onset of formation of the recirculation zone.

[2]Only premixed flames exhibit propagating wave behavior. Non-premixed flames do not propagate because they are controlled by molecular mixing of the fuel and the oxidizer.

vant to combustion and little was known about them. Moreover, the theoretical implication of the turbulent flame speed is a controversial topic with little consensus on its practical implementation. Because the low swirl combustion concept was conceived for basic laboratory research, on inception, investigation of its operating principle, overall flame behavior, and turbulent flow features with sophisticated laser methods was a top priority. The analyses quantified the fundamental characteristics of low swirl flows and produced an analytical model to prove why this new approach is robust. The basic knowledge also provided the scientific underpinning to guide development for gas turbines.

Low-swirl Flame Stabilization Principle and Engineering Guidelines

The most distinct characteristic of the LSI is a detached flame that is lifted above its exit (Fig. 2). This feature is quite unnerving to engineers who consider lifted flames to be inherently unstable, because they learned from combustion texts that flame detachment from a flame holder is a prelude to combustion instability and flameout. The LSI squelch this notion by demonstrating that a fundamental change from recirculating to non-recirculating divergent flow offers a much more robust configuration that allows the weak ultra-lean premixed turbulent flame to operation over a wider range of conditions including those that achieve near zero emissions levels of <2 ppm NO_x and CO.

The LSI (Fig. 1 & Fig 7 left) has a simple design that features an annulus vane swirler surrounding a cylindrical center channel. The center channel allows a portion of the reactants to pass without being swirled. The centrifugal forces of the swirling flow acting on the un-swirling center core create flow divergence downstream of the exit. In Figure 7 bottom left, the divergent nature of the flowfield in the nearfield region at x <10 mm is illustrated by streamlines that spread outward above x = 0. The rate of flow divergence, i.e. the spreading rate, is a LSI design parameter proportional to the ratio of the unswirled and the swirled flows. Flow divergence creates a flowfield where the axial velocity decays linearly with increasing x. When the velocity at the exit is maintained higher than the turbulent flame speed, S_T, the flame rides on this velocity "down-ramp" and self propels at the position where the local flow velocity is equal and opposite to S_T.

The divergence rate is adjustable via the parameters that define the LSI swirl number [Cheng et al., 2000]

Equation 1: $$S = \frac{2}{3}\tan\alpha \frac{1 - R^3}{1 - R^2 + [m^2(1/R^2 - 1)^2]R^2}$$

Here $\propto$ is the vane angle, $R = R_c/R_i$, where R_c and R_i are the corresponding radii of the center-channel and the injector (Fig. 7 top left), and $m = m_c/m_s$ represents the flow-split between the unswirled and the swirled flow passages where m_c and m_s are respectively the mass fluxes through the center-channel and the swirl annulus. The presence of m in Eq (1) distinguishes it from the swirl number definition for high-swirl injectors (Fig. 7 right column). When m = 0, i.e. a solid centerbody, Eq (1) reduces to the swirl number definition for high-swirl injectors. m in a LSI can be varied quite conveniently by placing a perforated plate over the open center-channel to create aerodynamic drag. m is then the ratio of the drag coefficients (or pressure drops) for the perforated plate and the swirl vanes. A very convenient means to vary the LSI swirl number, S, is by changing the blockage ratios or hole sizes of the perforated plate

The engineering guideline for the LSI is specified in terms of a range of swirl number ($0.4 < S < 0.55$), and swirler recess ($2 < L_i/R_i < 3$). Since the LSI uses the swirler

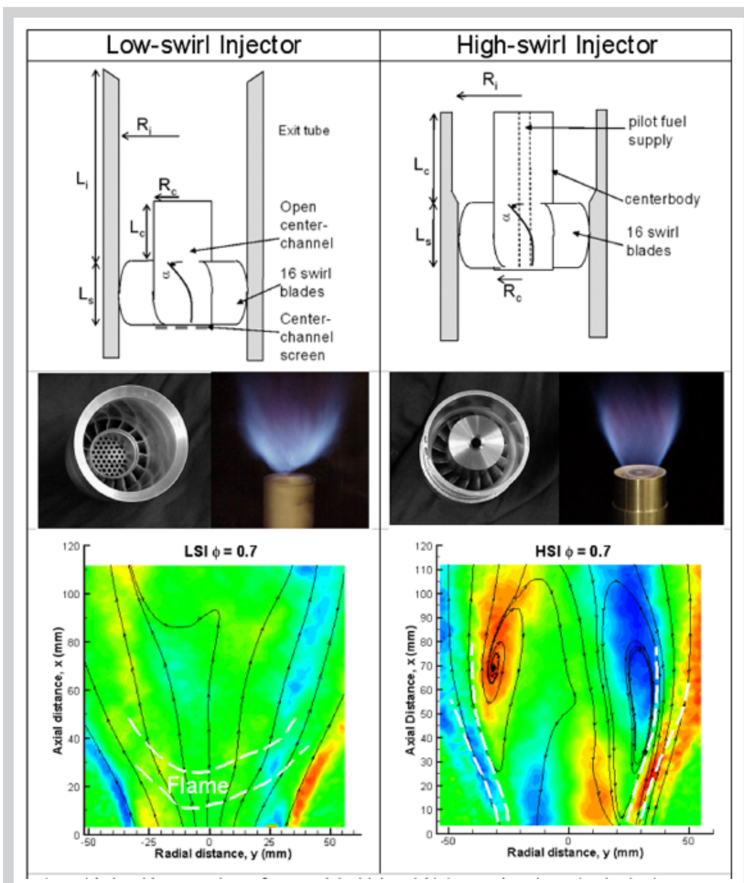

Figure 7 Side-by-side comparison of LSI and the high swirl injectors the schematics (top), pictures (middle) and mean streamlines obtained from PIV measurements (bottom).

designed for SoLoNOx, two of the three parameters in Eq (1) are fixed, i.e. $\propto = 40^{o}$ and $R = 0.63$. To meet the design criteria, a 58% blockage screen rendering S = 0.54 and an exit tube of $L_i = 9.5$ cm were used in its first prototype (fig. 7 left). To a casual observer, the LSI has a striking resemblance to the high-swirl injector (Fig. 7 right). The key and fundamental difference is the high-swirl injector has only one flow passage, and its solid centerbody promotes flow recirculation in its wake. When the centerbody is removed and replaced by an open channel, the unswirled flow in the center of the LSI prevents vortex breakdown to inhibit recirculation. The drastic differences in the flowfields of the LSI and the high swirl injectors are shown by their mean streamlines at the bottom of fig 7. The LSI's smooth streamlines are in stark contrast to the tightly coiled-up streamlines formed in the recirculation zone of the high-swirl injector.

The LSI is implemented in the Solar Turbines' Taurus 70 (T70) gas turbine (Fig. 3). Introduced in 1995, T70 is rated for 7.7 MW of electricity production from natural gas. Its combustor section is made up of an annulus combustor liner (chamber) fitted with twelve SoLoNOx injectors operating in high-swirl combustion mode. T70 with $SoLoNO_x$ guarantees emissions at two levels: < 25 ppm NO_x and CO <50 ppm or <15ppm and <25 ppm CO. The development of LSI for T70 is one of four R&D projects supported by the U.S. DOE Low Emissions Turbine Program (see matrix table). The Program's metrics are:

- < 5 ppm NO_x and < 10 ppm CO
- Pressure drop across injector < 4% of total operating pressure (maximum 16 atm)
- Durable for more than 8,000 hours continuous operation
- No more than 10% cost increase in engine fabrication and operation
- Consideration for backup fuel operation
- No negative impact on gas turbine performance

The first LSI prototype (flg. 5 right) was designed using the engineering guidelines and its validity at gas turbine operation was confirmed by testing with a cylindrical combustor liner at full load (800F, 15 atm) and partial load (45°F, 6 atm) conditions of the T70. Its NO_x emissions are 60% lower than those of the high-swirl injector (Fig 8). Therefore, the LSI can attain ultra-low emissions at conditions farther away from the lean flame blow-off limit and so avoids combustion oscillations [Johnson et al., 2004]. The lowest levels (<2 ppm) of NO_x and CO are comparable with those from much more costly and less durable catalytic options.

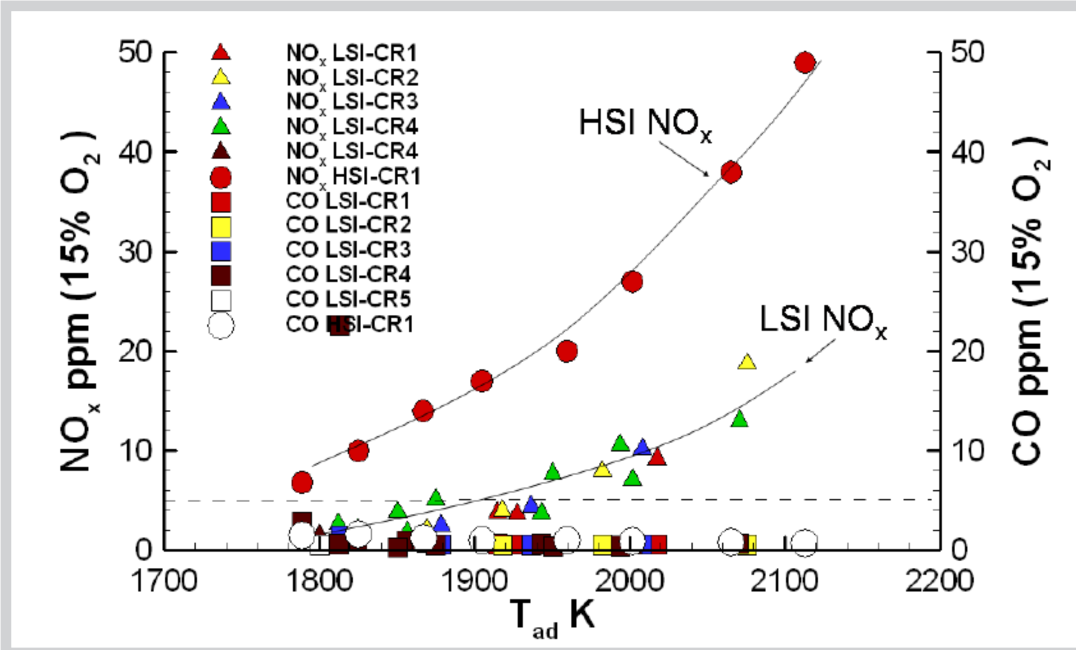

Figure 8 At the same adiabatic flame temperature, T_{ad}, NO_x emissions form natural gas LSI is 2.5 times less than the conventional high-swirl injector. The LSI NO_x emissions data were obtained from single injector tests at partial and full load conditions making it the first combustion technology to offer ultra-low emissions at lowl load

Further development of an engine-ready LSI includes a simple fuel spoke premixer similar to the one for current SoLoNO$_x$ engines and a central pilot to facilitate load following and responding to off-normal operating conditions (Fig. 1). As seen in Fig. 5, the fully functional LSI assembly is the same size and form as the SoLoNO$_x$ injector. In engine tests, the LSI shows emissions levels below 5 ppm NO_x and meets the DOE Low Emissions Turbine Program target. The engine tests proved that the implementation of the LSI is low cost and free of concerns about control needs, durability and maintenance. Work is underway to fine-tune the LSI design to achieve a near zero emission target of <2 ppm NO_x with natural gas in T70 and configure the premixer to accommodate the higher fuel volume for the bio- and waste gases.

Analytical Model Relating Flowfield and Flame Characteristics

Knowledge obtained from laboratory experimentation and data analyses explains how the LSI remains robust regardless of bulk flow velocities[3], U_o, fuel types,

[3]Bulk flow velocity is calculated based on the total volumetric flow rate of the reactants divided by the cross sectional area of the injector. It is a reference to the power output, i.e. load, of the injector.

flame properties and inlet thermodynamics conditions. The studies show that a linear coupling of the flow structures, turbulence intensity and the turbulent flame speed is the reason for its exceptional capability. As discussed earlier, flow divergence is the basic flow structure of the low swirl flame stabilization method. Recent laboratory experiments using particle image Velocimetry showed how the LSI flowfield evolves with bulk velocity, U_o [Cheng et al., 2006]. Data analysis revealed that the divergent region exhibit self-similar behavior. This means that the size and shape of the divergent flow do not change with U_o. Thus the divergence rate (i.e. the linear decay of the axial velocity, dU/dx) when normalized by U_o is a constant. Concurrently, the turbulent flame speeds, S_T, correlates linearly with the turbulence intensity, u' according to $S_T = S_L + K u'$ where S_L is the laminar flame speed and K is an empirical constant. Therefore, a balance equation can be written for the velocity at the leading edge of the flame brush, x_f expressed in terms of the velocity decay, dU/dx, U_o and S_T.

Equation 2: $$1-\frac{dU}{dx}\frac{(x_f-x_o)}{U_o}=\frac{S_T}{U_0}=\frac{S_L(1+Ku')}{U_o}$$

Here x_o is the virtual origin of the divergent flow and has a negative value. Self-similar means that $dU/dx/U_o$ is constant. By invoking the turbulent flame speed correlation, the second term on the far RHS of Eq. 2, $K\, u'/U_o$, is a constant because turbulence generated by the perforated plate is isotropic and u' scales linearly with U_o. The first term on the far RHS tends to a small value for large U_o because typical range of SL for hydrocarbons is from 0.2 to 0.7 m/s. Therefore, Eq 2 predicts that the LSI flame position remains stationary when U_o is high and is not sensitive to variations in the fuel/air ratio due to a small contribution from S_L. It also shows that the flame positions can be adjusted by varying the divergence rate (i.e. changing the swirl number S)

Eq. 2 provides an analytical model for the LSI flame/flowfield interaction processes. Though it is derived from laboratory experiments at velocities well below the typical turbine conditions of $65 < U_o < 85$ m/s, the trends observed in rig-tests and engine tests provide qualitative support to its validity. In our continuing effort to gain further insight into the fuel effects on LSI, a recent study shows that the turbulent flame speeds for hydrocarbons such as propane and ethylene, and hydrocarbons

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[4]Linear dependency of S_T on u' is not universal as S_T correlations in other flame stabilization methods such as high-swirl injectors or piloted flames tend to be non-linear and show "bending."

diluted with carbon dioxide or nitrogen have the same correlation constant as for natural gas [Littlejohn and Cheng, 2006]. This suggested that the LSI should be operable with these fuels without requiring significant modification. Recent rig-tests at Solar Turbine with low-Btu fuels at 40% of the heat content of natural gas show this to be the case.

By encapsulating the fundamental relationships between turbulence, aerodynamics, thermodynamics and combustion chemistry the analytical model for LSI is a simple and important design tool for its scaling and adaptation to fuel flexible gas turbines large or small. It gives a first order estimation on how the flame responses to fuel properties and points to what design changes would be need to accommodate them. In contract, an analytical model for high swirl injectors is not available due to its highly non-linear flow and flame processes, elaborate and time consuming computational fluid mechanics is required to predict and gain insight on the flame and flowfield interactions. The fact that the development of the LSI did not require computational fluid mechanics attests to the significant value of the scientific underpinning and a simple model to provide useful insight and guidance.

Delivers Exceptional Performance LSI Flowfield

Eq (2) also explains how the LSI responds to load changes and prevents flame flashback. As flow velocity changes with load, the structure of the divergent flow remains unchanged, but turbulence level increases and decreases accordingly. The flame "rides" the divergent flow and burns faster or slower synchronously with the flow velocity because turbulence gives critical feedback to the flame. When U_o is sufficient high, the flame remains stationary regardless of the flow velocity as demonstrated by Eq 2.

The LSI flowfield also addresses the important operational and safety concerns. The flame does not flashback because it cannot propagate faster than the velocity at the exit. The exception is when the flow velocity is at the same order as the laminar flame speed, S_L and Eq 2 gives an estimate of the bulk flow velocity where flame-back can occur. Blow off is also mitigated because the flame retreats to a lower velocity region of the divergent flow when a sudden decrease in the stoichiometry (i.e. lean out) occurs. Additionally, the flame adapts to mixture inhomogeneity or slight flow transients by shifting its position and minimizes the likelihood of catastrophic flameout. The LSI flame stabilization mechanism is self-adjusting and enables the flame to withstand transient and changes in mixture and flow conditions.

The LSI divergent flowfield also account for its exceptional emission trend. As shown by the results from a recent laboratory investigation (Fig. 9) the NO_X emissions from pure hydrocarbons and diluted hydrocarbons have log-linear dependency on the adiabatic flame temperature. Moreover, the NO_X concentration and the log-linear dependency are the same for flames at atmospheric conditions and at the elevated temperatures and pressures conditions of gas turbines. The important implication is that the NO_X emission of the LSI is predictable. This feature is

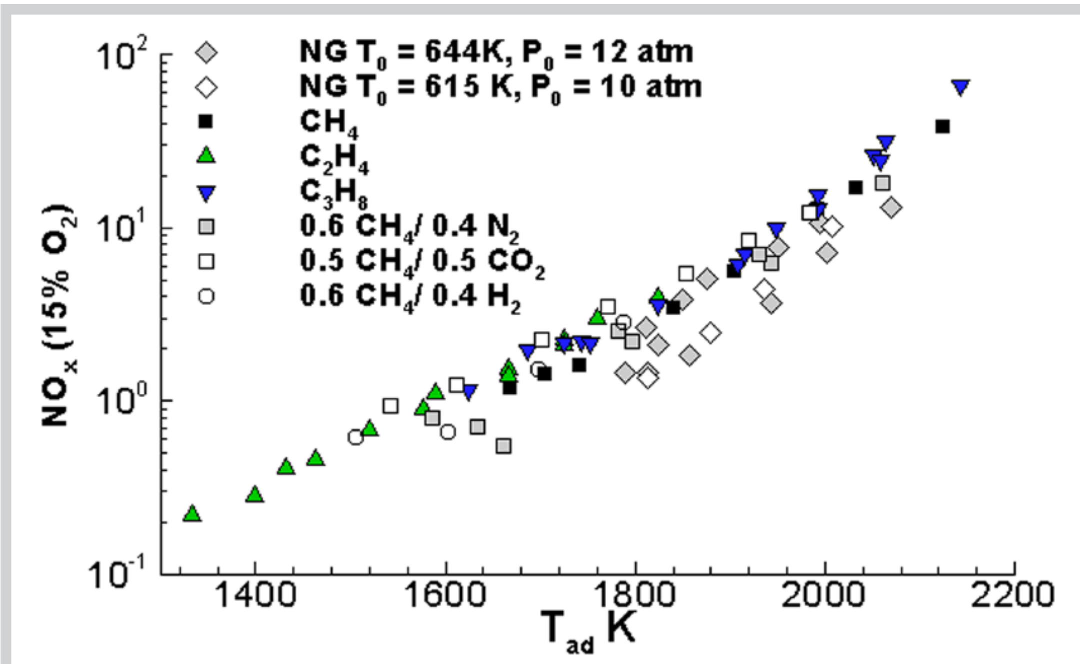

Figure 9 NO_X emissions of LSI from pure and diluted hydrocarbon fuels shows its log-linear dependence on the adiabatic flame temperature T_{ad}.

unique because a direct correlation between NO_X emissions and adiabatic flame temperature do not exist for other gas turbine injector designs. NO_X prediction usually involves extensive computational and analytical efforts. The log-linear NO_X emission dependency in LSI seems to be a consequence of the absence of strong recirculation. Studies have shown that NO_X concentrations increase with increasing residence time in the hot products. Without flow recirculation, the residence time of the flow in the hot products is short. Whereas in other designs such as the high swirl injectors NO_X concentrations are influenced by the prolonged residence time associated with non-linear flowfield characteristics such as flow recirculation.

To date, combustion oscillation characteristics if the LSI is the most significant outstanding fundamental issue. The interesting question from both the scientific and technological perspectives is whether or not the absence of a large recirculation zone in the LSI will have an influence on the combustion oscillation characteristics. Rig-tests and engine tests of the LSI indicate the absences of a strong characteristics acoustic signature from the flame. Through these observations are encouraging, the combustion oscillation characteristics of LSB need to be investigated more systematically to gain a basic understand for addressing issues that may arise when the technology is adapted for more complex systems such as IGCC gas turbines. The combustion research community is interested in this problem and is developing plans to conduct a direct comparison between the combustion oscillation characteristics of the LSI with the high-swirl injector.

Laboratory Studies for IGCC Development

Eq 2 shows that the turbulent speed S_T is the leading order combustion parameter for LSI adaptation to different gaseous fuels. But the study of S_T is still an active research area and data for the fuels relevant to IGCC such as syngases and hydrogen are unavailable. But a lack of scientific S_T data does not present a significant hurdle because laboratory experiments coupled with the analytical model can provide useful guidance on how to adjust the LSI for the slower and faster burning fuels. There are, of course, other combustion parameters such as heat release ratio, combustion intensity and preferential diffusion of the fuel components that need to be considered. From our studies of CH_4, C_2H_4, C_3H_8, and H_2 flames, contributions from these other factors are of lower order.

A recent laboratory study shows that the LSI is amenable to burning pure H_2 and H_2 diluted with an inert gas such as N_2.[Cheng and Littlejohn, 2007]. The velocity data showed that the basic LSI mechanism is not affected by the differences in the flame properties of hydrocarbons and H_2. The flowfields of the H_2 flames are self-similar having the same features found in hydrocarbon flames. The turbulent flame speeds of the H_2 flames correlate linearly with turbulence intensity, u'. However, the value of the correlation constant is higher than the value determined for hydrocarbon flames (fig. 10). According to Eq 2, a lower divergent rate is required for the H_2 fuels and this is confirmed by our finding that the optimum swirl number for H_2 is 0.51 down from 0.54 for the hydrocarbons. A S = 0.51 LSI has been tested successfully with high H_2 content fuels (>80%) in a gas turbine simulation at National

Energy Technology Laboratory in Morgantown, WV. These results proof the validity of the analytic model for LSI development and give strong support for the potential of the LSI technology for IGCC turbines.

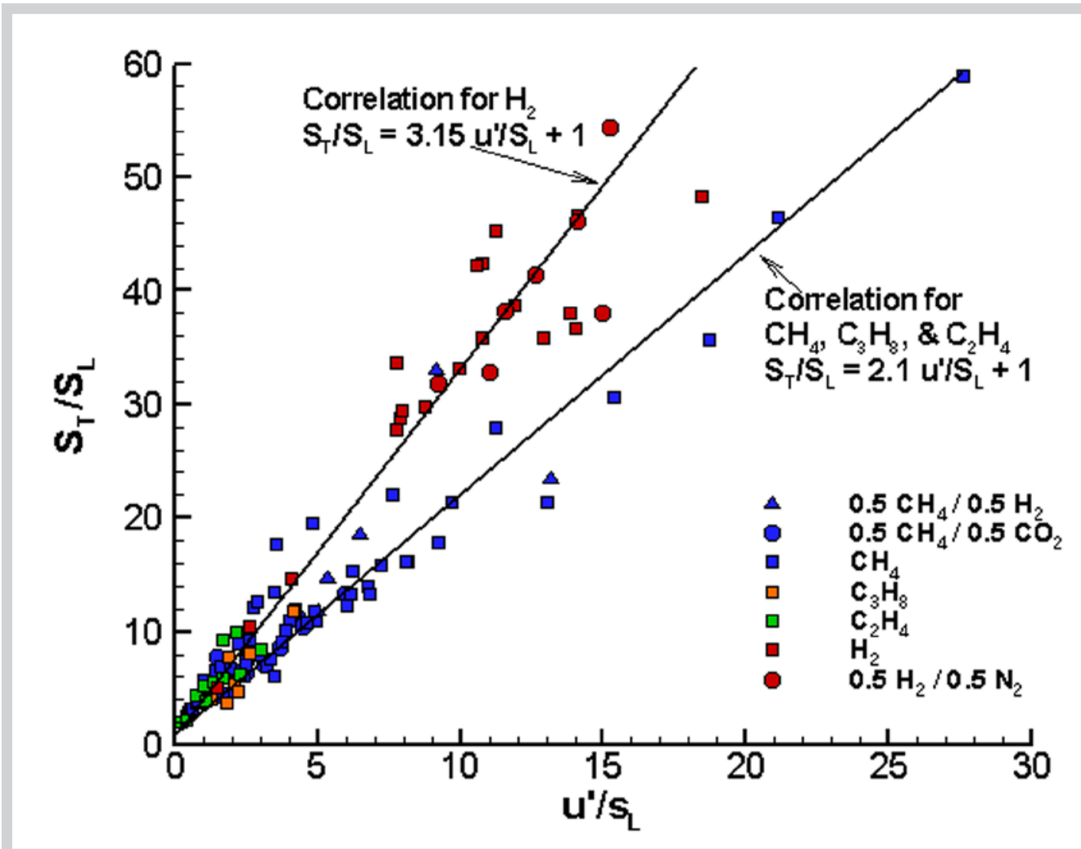

Figure 10 Comparison of turbulent flame speed, S_T, of H_2 and hydrocarbon flames.

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